Feasibility of the two-point method to determine the load-velocity relationship variables during the countermovement jump exercise

Abstract

Purpose: This study aimed to examine the reliability and validity of load-velocity relationship variables obtained through the two-point method using different load combinations and velocity variables.

Methods: Twenty men performed two identical sessions consisting of two countermovement jumps against four external loads (20-40-60-80 kg) and a heavy squat against a load linked to a mean velocity of 0.55 m·s^{-1} (load$_{0.55}$). The load-velocity relationship variables (load-axis intercept [L_0], velocity-axis intercept [v_0], and area under the load-velocity relationship line [A_{line}]) were obtained using three velocity variables (mean velocity [MV], mean propulsive velocity [MPV], and peak velocity [PV]) by the multiple-point method including (20-40-60-80-load$_{0.55}$) and excluding (20-40-60-80) the heavy squat, as well as from their respective two-point methods (20-load$_{0.55}$, and 20-80).

Results: The load-velocity relationship variables were obtained with an acceptable reliability (CV≤7.30%; ICC≥0.63). The reliability of L_0 and v_0 was comparable for both methods (CV$_{ratio}$=1.11-1.12), but the multiple-point method provided A_{line} with a greater reliability (CV$_{ratio}$=1.26). The use of a heavy squat provided the load-velocity relationship variables with a comparable or higher reliability than the use of a heavy countermovement jump load (CV$_{ratio}$=1.06-1.19). The PV provided the load-velocity relationship variables with the greatest reliability (CV$_{ratio}$=1.15-1.86) followed by MV (CV$_{ratio}$=1.07-1.18), and finally MPV. The two-point methods only revealed an acceptable validity for MV and MPV (ES≤0.19; r≥0.96; CCC≥0.94).

Conclusions: The two-point method obtained from a heavy squat load and MV or MPV is a quick, safe, and reliable procedure to evaluate the lower-body maximal neuromuscular capacities through the load-velocity relationship.

Keywords: force-velocity relationship; mean velocity; multiple-point method; peak velocity: velocity-based training.

1. Introduction

Velocity-based training (VBT) has been popularized among strength and conditioning professionals due to the increasing affordability of velocity monitoring devices[1] and its relevant and abundant practical applications.[2] For example, individualized load-velocity (L-V) relationships are used to regulate the training intensity,[3,4] quantify training-induced fatigue,[5,6] and assess changes in neuromuscular performance after training interventions.[7,8] Note also that individualized L-V relationship has been recommended over the generalized L-V relationship equations because the velocity associated with each relative load is subject-specific.[2] Furthermore, a novel application of the L-V relationship consists of determining the L-V relationship variables (load-axis intercept [L_0], velocity-axis intercept [v_0], and the area under the L-V relationship line [$A_{line} = L_0 \cdot v_0/2$]), which may be accurate indicators of the maximal capacities of producing force, velocity, and power, respectively.[9] In comparison to the force-velocity (F-V) relationship parameters (see Jaric[10] for further details), the assessment of the L-V relationship variables may be simpler and more reproducible because i) the force output does not need to be computed for the modeling, and ii) the extrapolation needed from the experimental points to v_0 is reduced because only the external load lifted is considered for the analysis. However, little information is available in the literature concerning the reliability and concurrent validity of the L-V relationship variables.[9]

The countermovement jump (CMJ) is commonly used to evaluate neuromuscular function of lower-body muscles.[11–13] The CMJ testing procedures have typically consisted of the assessment of mechanical variables (force, velocity, and power) against individual loads.[14,15] More recently, the F-V relationship has been modelled through simple linear regressions by collecting force and velocity outputs against multiple loads (i.e., *multiple-point method*).[11,12,16,17] However, since the F-V relationship in multi-joint tasks is highly linear,[10] it is generally accepted that the same F-V relationship parameters could be obtained more efficiently (i.e., less time and fatigue) from the modeling of the force and velocity outputs against only two distant loads (i.e., *two-point method*).[18–20] Specifically, in the CMJ exercise, to maximize the accuracy of the F-V relationship parameters the two-point method should be based on the minimum possible loading condition and a CMJ against a load that allows reaching a jump height of about 10 cm.[19] Previous studies have sought to identify the optimal combination of experimental points (i.e., loads) to determine the F-V relationship in exercises such as vertical jumping,[19] bench press throw,[21] or cycling.[22] However, no study has examined whether the two-point method could also provide L-V relationship variables with an acceptable reproducibility and concurrent validity. For example, it could be of interest to examine the feasibility of two-point methods differing in the magnitude of the heavy load (heavy squat *vs.* heavy CMJ) to determine the variables derived from the L-V relationship.

The determination of the F-V and L-V relationships require the assessment of lifting velocity under two or more loading conditions.[23] Therefore, another important factor that could affect the reliability of the outcomes of the F-V and L-V relationships is the velocity variable used.[11,12] For example, previous studies have shown that the F-V relationship parameters can be obtained with an acceptable reliability during the CMJ and squat jump (SJ) exercises using both the mean velocity (MV) and peak velocity (PV).[11,12] Although in the study of Cuk et al.[11] the MV showed to be more reliable than PV, the study of García-Ramos et al.[12] reported contrasting results (i.e. PV was more reliable than MV). Moreover, a recent study by Kotani et al.[24] has discouraged the use of the F-V and L-V profiles to make training decisions because their outcomes obtained using both MV and PV were generally unreliable during the SJ exercise. These suggestions were made despite that both velocity variables being obtained with a high reliability at each load and the outcomes of the F-V and L-V profiles did not differ significantly between sessions. Indeed, all the aforementioned studies have used force platforms to determine these profiles. It should be noted that outputs could be obtained with a lower reliability by force platforms compared to linear position/velocity transducers due to the greater manipulation of the raw data needed to obtain the variable of interest.[25] Therefore, further research is required to determine the between-session reliability of L-V relationship variables when velocity outputs are recorded with other devices such as linear position/velocity transducers that are the technology most used when implementing VBT.[1] Since previous studies have shown during the loaded CMJ and SJ exercises a greater reliability for PV compared to MV and mean propulsive velocity (MPV) when recorded by linear position/velocity transducers across a range of loads,[26,27] it is also plausible that PV provides the variables derived from the L-V relationship with a higher reliability during jumping tasks. However, the lack of agreement in the literature highlights the need for further research on this topic.

To address the existing gaps in the literature, we assessed, on two separate occasions, the variables derived from the L-V relationship during the CMJ exercise using different load combinations and velocity variables. The main aim was to examine the between-session reliability and concurrent validity of the L-V relationship variables (L_0, v_0, and A_{line}) obtained by different two-point methods compared to their respective multiple-point methods. The secondary aims were to determine the effect of the magnitude of the heaviest load (heavy squat *vs.* heavy CMJ) and velocity variable (MV *vs.* MPV *vs.* PV) used for modeling the L-V relationships on the reliability of the L-V relationship variables. We hypothesized that the two-point methods would provide the L-V relationship variables with high and comparable reliability to that of the multiple-point methods, while their outcomes would be highly valid.[18,19] We also hypothesized a greater reliability i) when using the heavy squat load compared to the heavier CMJ load due to a greater distance between the experimental points and increased proximity of the heavier experimental point to L_0,[19,21] and ii) for PV compared to MV and MPV because PV can be obtained with a greater reliability during loaded vertical jumps.[26,27]

2. Methods

2.1. Subjects

Twenty resistance-trained men (age = 22.2 ± 1.8 years [range: 20-26 years], stature = 1.75 ± 0.06 m, body mass = 73.7 ± 8.2 kg; data presented as mean ± standard deviation [SD]) volunteered to participate in this study. Prior to data collection all subjects participated in a four-week training program (eight sessions) in which they performed the CMJ exercise at maximal intended velocity. No physical limitations, health problems or musculoskeletal injuries that could compromise testing were reported. Subjects were required to avoid any strenuous exercise over the course of the study, and they were informed of the procedures and signed a written informed consent form before initiating the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board.

2.2. Study design

A repeated-measures design was used to examine the between-session reliability and concurrent validity of the L-V relationship variables obtained by different two-point methods with respect to their multiple-point methods during the CMJ exercise. Subjects were tested on two sessions separated by seven days. Each session consisted of two CMJs against four external loads (20, 40, 60, and 80 kg) and a squat against an estimated load equivalent to a MV of 0.55 $m \cdot s^{-1}$ ($load_{0.55}$).[28] Data of both sessions were used for reliability analyses, but only the data of the second session was used for validity analyses. Testing sessions were conducted at the University's research laboratory, at the same time of the day for each subject (± 1 hour), and under similar environmental conditions (≈ 22º C and ≈ 60% humidity).

2.3. Procedures

Each testing session began with a standardized warm-up consisting of five minutes of jogging at a self-selected moderate pace, dynamic stretching, joint mobilization exercises, and one set of five repetitions of the CMJ exercise performed with increasing effort against an external load of 20 kg (mass of the unloaded Smith machine barbell). After warming-up, subjects performed two CMJs against four external loads (20, 40, 60, and 80 kg) and a squat against the $load_{0.55}$ (124.1 ± 17.5 kg [range: 90-160 kg]). The MV collected under the four external loads was used for modeling the individualized L-V relationships by a linear regression model, and the $load_{0.55}$ was calculated in each session from these relationships as the load associated with a MV of 0.55 $m \cdot s^{-1}$ (0.54 ± 0.05 $m \cdot s^{-1}$ [0.40-0.59 $m \cdot s^{-1}$]). A MV of 0.55 $m \cdot s^{-1}$ was set to obtain an experimental point close to L_0 but without exposing the subjects to an unnecessary risk of injury associated with maximal lifts.[28] The five loads were applied in an incremental order and the rest period between the repetitions performed with the same and different loads was set to one and three minutes, respectively. Subjects received velocity performance feedback immediately after completing each repetition to encourage maximal effort.[29]

The CMJ technique involved subjects standing with the knees and hips fully extended, feet approximately shoulder-width apart, and the barbell held across the top of the shoulders and upper back. Thereafter, subjects initiated a downward movement until reaching 90º knee flexion, followed immediately by a jump for maximum height. The execution technique for the $load_{0.55}$ was identical to the CMJ, involving upward movement at maximal intended velocity, although without lifting the toes off the ground. To ensure the 90º knee angle, subjects descended until touching an adjustable rod of a tripod with their glutei.[30] The 90º knee angle was individually measured with a manual goniometer and the height of the tripod was recorded and maintained for both testing sessions.

2.4. Measurement equipment and data analysis

Stature (Seca 202 Stadiometer; Seca Ltd., Hamburg, Germany) and body mass (TBF-300A; Tanita Corp of America Inc, Arlington Heights, IL) were measured at the beginning of the first session. A Smith machine (Multipower Fitness Line, Peroga, Murcia, Spain) was used in all sessions coupled with a linear velocity transducer (T-Force System; Ergotech, Murcia, Spain) that directly sampled the velocity-time data at a frequency of 1,000 Hz. Validity and reliability of the T-Force system have been reported elsewhere.[31] The T-Force software automatically calculated the three velocity variables: MV (i.e., average velocity from the first positive velocity until the velocity is 0 $m \cdot s^{-1}$), MPV (i.e., average velocity from the first positive velocity until the acceleration is lower than gravity [- 9.81 $m \cdot s^{-2}$]), and PV (i.e. the maximum instantaneous velocity value reached during the upward movement).

The L-V relationships were calculated considering the three velocity variables (MV, MPV, and PV) using four load combinations: i) multiple-point with heavy squat (i.e., 20-40-60-80-load$_{0.55}$), ii) multiple-point with heavy CMJ (i.e., 20-40-60-80), iii) two-point with heavy squat (i.e., 20-load$_{0.55}$), and iv) two-point with heavy CMJ (i.e., 20-80). A least-square linear regression model ($L[V] = L_0 - sV$) was used to determine the individualized L-V relationships, where L_0 represents the load at zero velocity and s is the slope of the L-V relationship.[8] The v_0 and A_{line} were then calculated as follows: $v_0 = L_0/s$ and $A_{line} = L_0 \cdot v_0/2$.[9] Only the repetition with the highest velocity value at each load was used for modelling the L-V relationships. Therefore, 12 L-V relationships (two methods [multiple-point and two-point] × two load combinations [heavy squat and heavy CMJ] × three velocity variables [MV, MPV, and PV]) were obtained (see **Figure 1** for further details).

[Figure 1]

2.5. Statistical analyses

Descriptive data are presented as means, SD, and range. The normal distribution of the data was confirmed using the Shapiro-Wilk test ($P > 0.05$). The strength of the L-V relationships modelled by the multiple-point methods was examined through the Pearson's product-moment correlation coefficient (r). Paired samples t-tests were used to compare the magnitude of the L-V relationship variables between both testing sessions. Between-sessions reliability was assessed by the coefficient of variation (CV = standard error of measurement / subjects' mean score × 100) and intra-class correlation coefficient (ICC; model 3.1) with their corresponding 95% confidence interval. Acceptable reliability was determined as a CV < 10% and ICC > 0.70.[19] The ratio between 2 CVs was used to compare the reliability between the 2 methods (multiple- and two-point), 2 load combinations (heavy squat and heavy CMJ), and 3 velocity variables (MV, MPV, and PV). The smallest important ratio between 2 CVs was considered to be higher than 1.15.[27] Paired samples t-tests, Cohen's d effect size (ES), r coefficients, and Lin's concordance correlation coefficient (CCC) were used to assess the concurrent validity of the two-point methods compared to their respective multiple-point methods. The criteria to interpret the magnitude of the ES was: *trivial* (< 0.20), *small* (0.20–0.59), *moderate* (0.60–1.19), *large* (1.20–2.00), or *very large* (> 2.00).[32] The strength of the r coefficients was interpreted as: *trivial* (0.00–0.09), *small* (0.10–0.29), *moderate* (0.30–0.49), *high* (0.50–0.69), *very high* (0.70–0.89), or *practically perfect* (> 0.90).[33] The criteria to interpret the CCC were as follows: *very poor* (< 0.70), *poor* (0.70-0.90), *moderate* (0.90-0.95), *good* (0.95-0.99), and *very good* (> 0.99).[34] The two-point methods were deemed to have an acceptable validity if the following criteria were met: from *trivial* to *small* ES (< 0.20), from *very high* to *practically perfect* correlations (r > 0.90), and from *moderate* to *very good* concordances (CCC > 0.90). The agreement between the multiple- and two-point methods was also quantified using the Bland-Altman 95% limits of agreement (LoA) technique (bias ± [1.96 × SD_{diff}]). The r coefficients were also used to explore the association of the same L-V relationship variables obtained using different velocity variables. All reliability assessments were performed by means of a custom Excel spreadsheet,[33] while other statistical analyses were performed using the software package SPSS (IBM SPSS version 22.0, Chicago, IL). Alpha was set at 0.05. *Post-hoc* statistical power was conducted using G*Power version 3.1.9.6 with an ES of 0.5 and alpha of 0.05, and revealed a 0.80 statistical power.

3. Results

All velocity variables reported an acceptable reliability for the four external loads (MV: CV = 2.48% [1.50-2.99%]; ICC = 0.89 [0.80-0.96]; MPV: CV = 3.00% [2.31-3.62%]; ICC = 0.86 [0.73-0.94]; PV: CV = 1.76% [1.41-2.02%]; ICC = 0.95 [0.91-0.97]). The strength of the individualized L-V relationships recorded from both multiple-point methods was *practically perfect* for the three velocity variables (MV: r = 1.00 [0.98-1.00]; MPV: r = 1.00 [0.97-1.00]; PV: r = 1.00 [0.98-1.00]).

The between-session reliability was generally acceptable for L_0 (CV = 5.31% [3.84-7.30%]; ICC = 0.80 [0.66-0.91]), v_0 (CV = 3.12% [1.76-4.27%]; ICC = 0.75 [0.63, 0.91]), and A_{line} (CV = 3.68% [2.79-4.86%]; ICC = 0.93 [0.86, 0.96]) (**Table 1**). The reliability comparisons revealed that i) the multiple-point method provided a comparable reliability for L_0 (CV_{ratio} = 1.12) and v_0 (CV_{ratio} = 1.11) and a greater reliability for A_{line} (CV_{ratio} = 1.26) compared to the two-point method, ii) the heavy squat load provided a comparable reliability for v_0 (CV_{ratio} = 1.07) and A_{line} (CV_{ratio} = 1.06) and a greater reliability for L_0 (CV_{ratio} = 1.19) compared to the heavy CMJ load, and iii) the PV provided all L-V relationship variables with greater reliability than the MV and MPV (CV_{ratio} ≥ 1.15), while the MV provided comparable reliability for L_0 and A_{line} (CV_{ratio} = 1.07) and a greater reliability for v_0 (CV_{ratio} = 1.18) compared to the MPV (**Figure 2**).

[Table 1]

[Figure 2]

The two-point methods revealed an acceptable validity compared to their respective multiple-point methods for MV and MPV (ES range = 0.01-0.19; r range = 0.96-1.00; CCC range = 0.94-0.99), but not for PV (ES range = 0.03-0.60; r range = 0.67-0.99; CCC range = 0.55-0.98) (**Table 2**). Finally, regardless of the method and load combination, the three L-V relationship variables revealed *nearly perfect* correlations between MV and MPV (r = 0.98 [0.95-1.00]), and *very high* correlations between PV and MV (r = 0.81 [0.61-0.94]) and between PV and MPV (r = 0.79 [0.58-0.92]).

[Table 2]

4. Discussion

This study was designed to examine the between-session reliability and concurrent validity of L-V relationship variables obtained from the two-point method with respect to the multiple-point method during the CMJ exercise using different load combinations and velocity variables. The main findings of this study revealed that i) the three L-V relationship variables were obtained with an acceptable reliability regardless of the method, load combination, and velocity variable, ii) both methods provided L_0 and v_0 with comparable reliability, but the multiple-point method provided A_{line} with a greater reliability, iii) the use of a heavy squat provided the L-V relationship variables with a comparable or higher reliability than the use of a heavy CMJ load, iv) the velocity variables could be ranked from the most to the least reliable as follows: PV > MV > MPV, and v) both two-point methods only revealed an acceptable concurrent validity compared to their respective multiple-point methods for MV and MPV. These results suggest that the two-point method obtained from a heavy squat load and MV or MPV is a quick, safe, and reliable procedure to evaluate the maximal neuromuscular capacities of lower-body muscles through the assessment of the L-V relationship variables.

It has been recently shown that the L-V relationship variables could be a simpler and more reproducible alternative than the F-V relationship parameters to estimate the upper-body maximal neuromuscular capacities.[9] However, further research is still needed to explore the reliability of this novel approach in other multi-joint tasks. Regardless of the method, load combination and velocity variable, the results of the present study revealed that the three variables derived from the L-V relationship (L_0, v_0, and A_{line}) were provided with an acceptable between-session reliability during the CMJ exercise. These results are in agreement with previous studies showing that the three F-V relationship parameters (F_0, v_0, and P_{max}) can be generally obtained with acceptable reliability (CV_{range} = 2.4-13.0%; ICC_{range} = 0.69-0.98) during CMJ and SJ exercises.[11,12] However, our results contrast with recent work that questioned the practical usefulness of the F-V and L-V profiles because their outcomes were not reliable (CV_{range} = 8.9-39.4%; ICC_{range} = 0.03-0.92) during the SJ exercise.[24] The discrepancy between the results of the present study and the Kotani's study[24] is probably due to i) the lack of familiarity of the subjects with the loaded SJ testing protocol (only one familiarization session), ii) the fatigue developed throughout the testing protocol (11 loading conditions), and iii) the device used to measure the velocity output (system center-of-mass velocity calculated from the force-time signal recorded by a force platform). Therefore, our study is the first to show that not only L_0 and v_0, but also the A_{line} can be obtained with acceptable reliability from the barbell's velocity recorded by a linear velocity transducer during the loaded CMJ exercise.

One important aspect when determining the F-V and L-V relationships is to find a testing protocol that allows to accurately determine their outcomes with minimum effort and time.[23] Supporting partially our main hypothesis, the two-point method generally revealed the L-V relationship variables with a comparable between-session reliability and an acceptable concurrent validity compared to the multiple-point method when using mean velocities. These findings are in line with previous studies showing that the L-V relationship modeled through the two-point methods can be used to estimate the one repetition maximum (1RM) with high precision in various upper-body resistance training exercises.[35,36] More importantly, our results are in agreement with previous studies showing that the two-point method is a reliable and valid procedure for the assessment of muscle mechanical capacities through the F-V relationship parameters obtained during the CMJ and SJ exercises.[18–20] Due to the high linearity of the L-V relationship ($r \geq 0.97$), it is evident that the addition of intermediate loads should not meaningfully improve the precision of the relationship modeling compared to using only the two most distant experimental points.[23] However, it is worth noting that the reliability of the A_{line} was greater for the multiple-point method than for the two-point method, likely because the error in determining A_{line} is affected by the errors of both L_0 and v_0. Nonetheless, our study provides additional evidence that the two-point method is not only a reliable and valid alternative to the multiple-point method when using mean velocities, but also a quicker and less prone to fatigue procedure to evaluate the lower-body maximal neuromuscular capacities through the L-V relationship obtained during the loaded CMJ exercise.

The distance between the two most distant experimental points and the proximity of the experimental points to the axis intercepts are two of the most important methodological factors to obtain accurate F-V relationship parameters.[23] However, there is little information regarding the effect of the magnitude of the heaviest load in the modeling of the L-V relationship. Supporting our secondary hypothesis, the reliability of the L-V relationship variables was generally greater for the heavy squat load compared to the heavy CMJ load, likely due to the greater distance between the experimental points and increased proximity of the heavier experimental point to L_0. These results are in agreement with Rivière et al.[37] who found that the goodness of fit of the F-V relationship obtained during the loaded SJ exercise did not differ with or without including the squat 1RM point. Similarly these data agree with García-Ramos et al.[19] and Šarabon et al.[18] who observed that the two-point method based on the heavy CMJ load provided a high between-session reliability and concurrent validity with respect to the multiple-point method to determine the F-V relationship parameters during the SJ and CMJ exercises. In contrast, Šarabon et al.[18] found a *poor-to-fair* validity for the two-point method based on an isometric maximal voluntary contraction task (squat exercise performed at 30º, 60º, and 90º knee angles). Such discrepancies may be partially attributed to the different force production modalities that represents a dynamic (full range of knee extension) and isometric task (fixed knee angle).[37] In fact, it has been shown the a weak association between F_0 and the maximal isometric voluntary contraction during the squat exercise.[38] Collectively, our results highlight that the two-point method based on the heavy squat load is more reliable, equally valid, and potentially safer than the generally used two-point method based on a heavy CMJ load.

A recent systematic review has shown that linear position/velocity transducers are the most used and accurate devices for measuring barbell velocity during resistance training.[1] Note that, although both systems consist of a sensor with a cable that is attached directly to the collar of the barbell, the linear velocity transducer measures barbell velocity by recording electrical signals proportional to the cable extension velocity, while the linear position transducer measures barbell velocity from the differentiation of the cable displacement with respect to time.[39] The three velocity variables examined in this study (MV, MPV and PV) are commonly recorded through linear position/velocity transducers for modeling the F-V and L-V relationships.[2,40] However, no study has examined which velocity variable provides the outcomes of the L-V relationship with the highest reliability. Since previous studies have shown a higher reliability for PV compared to MV and MPV across a range of relatives loads during CMJ and SJ exercises,[26,27] we hypothesized that PV would be the most reliable variable to determine the L-V relationship variables. Supporting our hypothesis, PV was the most reliable variable, followed by MV, and finally MPV. These results are in consensus with a previous study that examined the reliability of the velocity variables across the whole L-V relationship spectrum during the bench press throw exercise.[40] However, regardless of the load combination, the concurrent validity of the two-point method with respect to multiple-point method was only acceptable for MV and MPV variables. The lower concurrent validity observed for PV may be attributed to a lower linearity of the L-V relationship.[40] It is important to note that the L-V relationship variables obtained using the three velocity variables were strongly correlated (especially between MV and MPV). Therefore, since the three variables provide similar information, the MV could be recommended to obtain the L-V relationship variables during the CMJ exercise due to its greater reliability and concurrent validity.

There are several limitations that need to be acknowledged. First, the use of a relatively small sample size of resistance-trained men, which were all highly familiarized with the loaded CMJ performed at maximal intended velocity, makes the extrapolation of the present findings to less skilled populations (e.g., untrained subjects) challenging. Second, the generalizability of current results may be also limited to the use of a Smith machine, which restricts the movement of the barbell to the vertical direction, as well as to the use of a linear velocity transducer. This is because the mechanical variables recorded by a linear velocity transducer during the CMJ exercise can be obtained with a somewhat higher reliability using a Smith machine compared to free-weights.[25] In addition, although the velocity measurements are highly related between force platforms and linear position/velocity transducers,[41] their outcomes should not be used interchangeably due to systematic differences.[25] Third, the minimum load was set to 20 kg (mass of the unloaded Smith machine barbell) to keep the same execution technique for all tested loads. It is possible that by including a jump against a very light load (e.g., 0.5 kg) the reliability of v_0 could be increased by reducing the extrapolation to the velocity intercept. Finally, the two-point method was derived from a testing protocol based on multiple loads. Therefore, although a high reliability and validity of the F-V relationship parameters has been observed when the two-point method was applied in in field conditions (only two loads applied) in the leg cycle ergometer exercise,[42] further research is warranted to explore the feasibility of the L-V relationship variables when only two loads are applied in the testing protocol.

In conclusion, the two-point method provided the L-V relationship variables with an acceptable reliability regardless of the load combination and velocity variable. However, the concurrent validity of the two-point method with respect to the multiple-point method was only acceptable for mean velocities. We recommend that practitioners use a heavy squat load and MV or MPV to model the L-V relationship through the two-point method during the CMJ. Moreover, although L-V relationship variables (L_0, v_0, and A_{line}) do not present clear physiological meaning, unlike the parameters derived from the F-V relationship (F_0, v_0, and P_{max}), this novel approach can provide practitioners with a simpler and more precise alternative due to the lower number of mechanical variables included in the modeling (force output is not considered) and the lower extrapolation from the experimental points to v_0 (only the external load lifted is considered in the analysis).

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Authors' contribution

A-PC and A-GR contributed to the conception and design of the study. A-PC organized the database and performed the statistical analysis. A-PC wrote the first draft of the manuscript. A-GR supervised the study. All authors (A-PC, R-RC, JFT-F, and A-GR) contributed to manuscript revision, read and approved the submitted version.

Competing interests

The authors declare that they have no competing interests.

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Figure captions

Figure 1. Load-velocity relationships obtained from the data averaged across the subjects modelled by the different two-point methods and their respective multiple-point methods using the mean velocity (upper panel), mean propulsive velocity (middle panel), and peak velocity (lower panel) during the countermovement jump exercise. Mean values are shown for the four external loads (20, 40, 60, and 80 kg) and the estimated load equivalent to 0.55 $m \cdot s^{-1}$ ($load_{0.55}$), while the error bars represent the standard deviation. Regression equations obtained from each individual method are also indicated (*r*, Pearson's correlation coefficient). L_0, load-axis intercept; v_0, velocity-axis intercept; A_{line}, area under the L-V relationship line.

Figure 2. Reliability comparisons between the different methods (multiple-point and two-points), load combinations (heavy squat and heavy countermovement jump [CMJ]), and velocity variables (mean velocity [MV], mean propulsive velocity [MPV], and peak velocity [PV]) for the load-axis intercept (L_0; upper panel), velocity-axis intercept (v_0; middle panel), and area under the load-velocity (L-V) relationship line (A_{line}; lower panel) obtained during the countermovement jump exercise. Bars represent the average coefficient variation (CV) values and their respective standard deviations obtained combining the two load combinations and three velocity variables for the method, the two methods and three velocity variables for the load combination, and the two methods and load combinations for the velocity variable. Numbers depict the ratio between two CV (CV_{ratio} = higher value / lower value), while meaningful differences in reliability (CV_{ratio} > 1.15) are indicated in bold.

Table 1. Between-session reliability of the load-velocity (L-V) relationship variables obtained from different methods, load combinations, and velocity variables during the countermovement jump (CMJ) exercise.

Method	Load combination	Velocity variable	L-V variable	Session 1 (Mean ± SD)	Session 2 (Mean ± SD)	*P*	CV (%) (95% CI)	ICC (95% CI)
Multiple-point	Heavy squat (20-40-60-80-load$_{0.55}$)	MV	L_0 (kg)	191.0 ± 23.5	184.2 ± 22.5	0.036	5.08 (3.87, 7.42)	0.84 (0.65, 0.93)
			v_0 (m·s^{-1})	1.61 ± 0.08	1.60 ± 0.09	0.413	3.05 (2.32, 4.45)	0.68 (0.35, 0.86)
			A_{line} (kg·m·s^{-1})	153.9 ± 21.3	147.0 ± 19.3	<0.001	3.07 (2.34, 4.48)	0.95 (0.89, 0.98)
		MPV	L_0 (kg)	176.6 ± 22.3	172.8 ± 21.1	0.167	4.79 (3.64, 6.99)	0.87 (0.69, 0.94)
			v_0 (m·s^{-1})	1.84 ± 0.09	1.80 ± 0.11	0.055	3.56 (2.71, 5.20)	**0.63 (0.27, 0.84)**
			A_{line} (kg·m·s^{-1})	162.8 ± 22.9	155.6 ± 20.8	<0.001	3.03 (2.30, 4.42)	0.96 (0.89, 0.98)
		PV	L_0 (kg)	195.2 ± 24.0	193.0 ± 22.2	0.367	3.84 (2.92, 5.61)	0.91 (0.78, 0.96)
			v_0 (m·s^{-1})	3.07 ± 0.17	3.03 ± 0.16	0.031	1.76 (1.34, 2.57)	0.91 (0.78, 0.96)
			A_{line} (kg·m·s^{-1})	300.0 ± 44.1	292.5 ± 38.4	0.016	3.02 (2.29, 4.41)	0.96 (0.90, 0.98)
	Heavy CMJ (20-40-60-80)	MV	L_0 (kg)	193.5 ± 20.2	184.9 ± 25.1	0.031	6.21 (4.72, 9.07)	0.75 (0.48, 0.89)
			v_0 (m·s^{-1})	1.60 ± 0.09	1.60 ± 0.11	0.731	3.23 (2.45, 4.71)	0.75 (0.47, 0.89)
			A_{line} (kg·m·s^{-1})	155.0 ± 17.3	147.2 ± 18.8	<0.001	3.77 (2.87, 5.51)	0.91 (0.79, 0.96)
		MPV	L_0 (kg)	170.0 ± 17.5	166.8 ± 20.4	0.331	5.96 (4.53, 8.71)	0.74 (0.45, 0.89)
			v_0 (m·s^{-1})	1.86 ± 0.12	1.82 ± 0.13	0.088	3.95 (3.00, 5.77)	**0.67 (0.34, 0.86)**
			A_{line} (kg·m·s^{-1})	158.3 ± 17.6	151.7 ± 18.9	<0.001	3.35 (2.54, 4.89)	0.93 (0.83, 0.97)
		PV	L_0 (kg)	184.1 ± 13.8	182.4 ± 18.3	0.490	4.22 (3.21, 6.17)	0.79 (0.54, 0.91)
			v_0 (m·s^{-1})	3.12 ± 0.20	3.08 ± 0.18	0.095	2.19 (1.67, 3.20)	0.89 (0.74, 0.95)
			A_{line} (kg·m·s^{-1})	287.0 ± 30.2	280.6 ± 31.6	0.020	2.79 (2.12, 4.08)	0.94 (0.86, 0.98)
Two-point	Heavy squat (20-load$_{0.55}$)	MV	L_0 (kg)	190.7 ± 25.6	184.5 ± 23.7	0.079	5.61 (4.27, 8.20)	0.83 (0.63, 0.93)
			v_0 (m·s^{-1})	1.60 ± 0.09	1.60 ± 0.10	0.783	3.37 (2.56, 4.92)	0.72 (0.41, 0.88)
			A_{line} (kg·m·s^{-1})	152.9 ± 23.8	147.3 ± 21.5	0.018	4.47 (3.40, 6.54)	0.92 (0.81, 0.97)
		MPV	L_0 (kg)	177.7 ± 24.5	174.4 ± 22.6	0.279	5.34 (4.06, 7.80)	0.86 (0.67, 0.94)
			v_0 (m·s^{-1})	1.87 ± 0.11	1.82 ± 0.12	0.084	3.94 (3.00, 5.76)	**0.64 (0.28, 0.84)**
			A_{line} (kg·m·s^{-1})	165.9 ± 26.6	159.0 ± 23.8	0.013	4.86 (3.70, 7.11)	0.91 (0.79, 0.96)
		PV	L_0 (kg)	187.8 ± 13.9	185.5 ± 18.2	0.370	4.40 (3.35, 6.43)	0.76 (0.49, 0.90)

		v_0 (m·s^{-1})	3.14 ± 0.20	3.10 ± 0.18	0.140	2.41 (1.84, 3.53)	0.86 (0.68, 0.94)
		A_{line} (kg·m·s^{-1})	294.8 ± 30.1	287.5 ± 32.1	0.014	2.96 (2.25, 4.32)	0.93 (0.83, 0.97)
Heavy CMJ (20-80)	MV	L_0 (kg)	196.7 ± 19.5	185.8 ± 26.6	0.023	7.30 (5.55, 10.67)	**0.66 (0.32, 0.85)**
		v_0 (m·s^{-1})	1.59 ± 0.09	1.60 ± 0.11	0.912	3.65 (2.77, 5.33)	0.71 (0.40, 0.88)
		A_{line} (kg·m·s^{-1})	156.7 ± 17.4	147.8 ± 19.8	0.001	4.73 (3.59, 6.90)	0.86 (0.69, 0.94)
	MPV	L_0 (kg)	173.7 ± 16.8	168.7 ± 21.8	0.170	6.50 (4.95, 9.50)	**0.69 (0.37, 0.87)**
		v_0 (m·s^{-1})	1.87 ± 0.12	1.83 ± 0.13	0.157	4.27 (3.25, 6.24)	**0.64 (0.28, 0.84)**
		A_{line} (kg·m·s^{-1})	162.1 ± 17.0	154.1 ± 19.7	<0.001	3.77 (2.87, 5.50)	0.91 (0.78, 0.96)
	PV	L_0 (kg)	196.2 ± 26.9	194.9 ± 23.6	0.646	4.49 (3.41, 6.56)	0.89 (0.75, 0.96)
		v_0 (m·s^{-1})	3.13 ± 0.18	3.08 ± 0.17	0.056	2.09 (1.59, 3.05)	0.88 (0.72, 0.95)
		A_{line} (kg·m·s^{-1})	307.5 ± 51.5	300.9 ± 43.0	0.127	4.28 (3.25, 6.25)	0.93 (0.84, 0.97)

SD, standard deviation; *P*, *P*-value obtained through a paired samples *t*-test; CV, coefficient of variation; ICC, intraclass correlation coefficient; 95% CI, 95% confidence interval; load$_{0.55}$, estimated load equivalent to 0.55 m·s^{-1}; MV, mean velocity; MPV, mean propulsive velocity; PV, peak velocity; L_0, load-axis intercept; v_0, velocity-axis intercept; A_{line}, area under the L-V relationship line. Bold numbers indicate an unacceptable reliability (CV > 10% and ICC < 0.70).

Table 2. Comparison of the load-velocity (L-V) relationship variables obtained by different two-point methods compared to their respective multiple-point methods for each velocity variable during the countermovement jump exercise.

Load combination	Velocity variable	L-V variable	*P*	ES	*r* (95% CI)	CCC (95% CI)	Bias (95% LoA)
Heavy squat (20-load$_{0.55}$)	MV	L_0 (kg)	0.675	-0.01	0.99 (0.98, 1.00)	0.99 (0.98, 1.00)	-0.1 (-3.9, 3.7)
		v_0 (m·s^{-1})	0.911	0.01	0.96 (0.90, 0.98)	0.95 (0.89, 0.98)	0.00 (-0.04, 0.04)
		A_{line} (kg·m·s^{-1})	0.792	-0.01	0.98 (0.94, 0.99)	0.97 (0.93, 0.99)	-0.1 (-5.7, 5.5)
	MPV	L_0 (kg)	0.105	-0.07	0.99 (0.96, 0.99)	0.98 (0.95, 0.99)	-0.5 (-5.3, 4.3)
		v_0 (m·s^{-1})	0.008	-0.19	0.96 (0.91, 0.99)	0.94 (0.86, 0.98)	-0.01 (-0.05, 0.04)
		A_{line} (kg·m·s^{-1})	0.029	-0.16	0.97 (0.91, 0.99)	0.94 (0.87, 0.98)	-1.2 (-9.3, 6.9)
	PV	L_0 (kg)	0.026	0.37	0.78 (0.51, 0.91)	0.71 (0.42, 0.87)	2.6 (-14.8, 20.0)
		v_0 (m·s^{-1})	< 0.001	-0.41	0.93 (0.82, 0.97)	0.85 (0.65, 0.94)	-0.02 (-0.13, 0.08)
		A_{line} (kg·m·s^{-1})	0.169	0.14	0.91 (0.79, 0.97)	0.89 (0.76, 0.95)	1.8 (-16.8, 20.3)
Heavy CMJ (20-80)	MV	L_0 (kg)	0.168	-0.04	1.00 (0.99, 1.00)	0.99 (0.99, 1.00)	-0.3 (-3.6, 3.0)
		v_0 (m·s^{-1})	0.834	0.01	0.99 (0.97, 1.00)	0.99 (0.97, 0.99)	0.00 (-0.02, 0.02)
		A_{line} (kg·m·s^{-1})	0.274	0.03	0.99 (0.99, 1.00)	0.99 (0.98, 1.00)	0.2 (-2.5, 2.9)
	MPV	L_0 (kg)	0.005	-0.09	0.99 (0.99, 1.00)	0.99 (0.97, 1.00)	-0.6 (-4.0, 2.8)
		v_0 (m·s^{-1})	0.012	0.07	0.99 (0.99, 1.00)	0.99 (0.98, 1.00)	0.00 (-0.02, 0.02)
		A_{line} (kg·m·s^{-1})	< 0.001	-0.12	0.99 (0.98, 1.00)	0.99 (0.96, 0.99)	-0.8 (-4.2, 2.6)
	PV	L_0 (kg)	0.005	0.60	0.67 (0.33, 0.86)	0.55 (0.20, 0.70)	4.3 (-18.9, 27.6)
		v_0 (m·s^{-1})	0.382	0.03	0.99 (0.96, 0.99)	0.98 (0.96, 0.99)	0.00 (-0.03, 0.04)
		A_{line} (kg·m·s^{-1})	0.002	-0.54	0.81 (0.57, 0.92)	0.67 (0.38, 0.84)	-7.0 (-41.5, 27.5)

Load$_{0.55}$, estimated load equivalent to 0.55 m·s^{-1}; MV, mean velocity; MPV, mean propulsive velocity; PV, peak velocity; L_0, load-axis intercept; v_0, velocity-axis intercept; A_{line}, area under the L-V relationship line; *P*, *P*-value; ES, Cohen's *d* effect size ([multiple-point method mean – two-point method mean] / SD both); *r*, Pearson's correlation coefficients; CCC, Lin's concordance correlation coefficient; 95% CI, 95% confidence interval; 95% LoA, 95% limits of agreement (± 1.96 standard deviation).

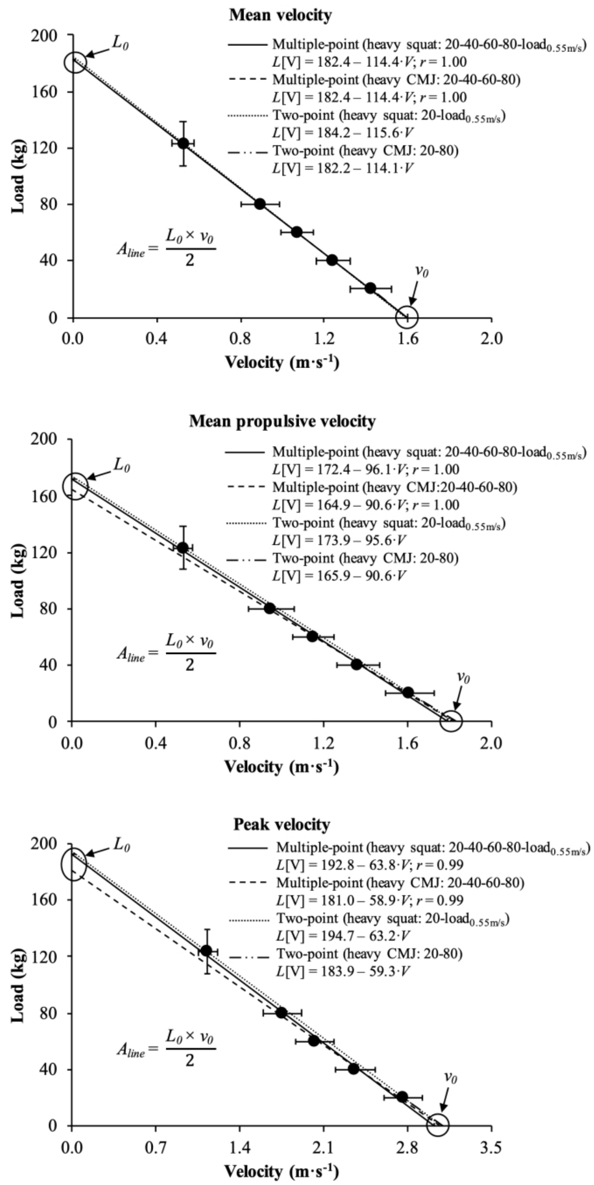

Figure 1. Load-velocity relationships obtained from the data averaged across the subjects modelled by the different two-point methods and their respective multiple-point methods using the mean velocity (upper panel), mean propulsive velocity (middle panel), and peak velocity (lower panel) during the countermovement jump exercise. Mean values are shown for the four external loads (20, 40, 60, and 80 kg) and the estimated load equivalent to 0.55 m·s-1 (load0.55), while the error bars represent the standard deviation. Regression equations obtained from each individual method are also indicated (r, Pearson's correlation coefficient). L0, load-axis intercept; v0, velocity-axis intercept; Aline, area under the L-V relationship line.

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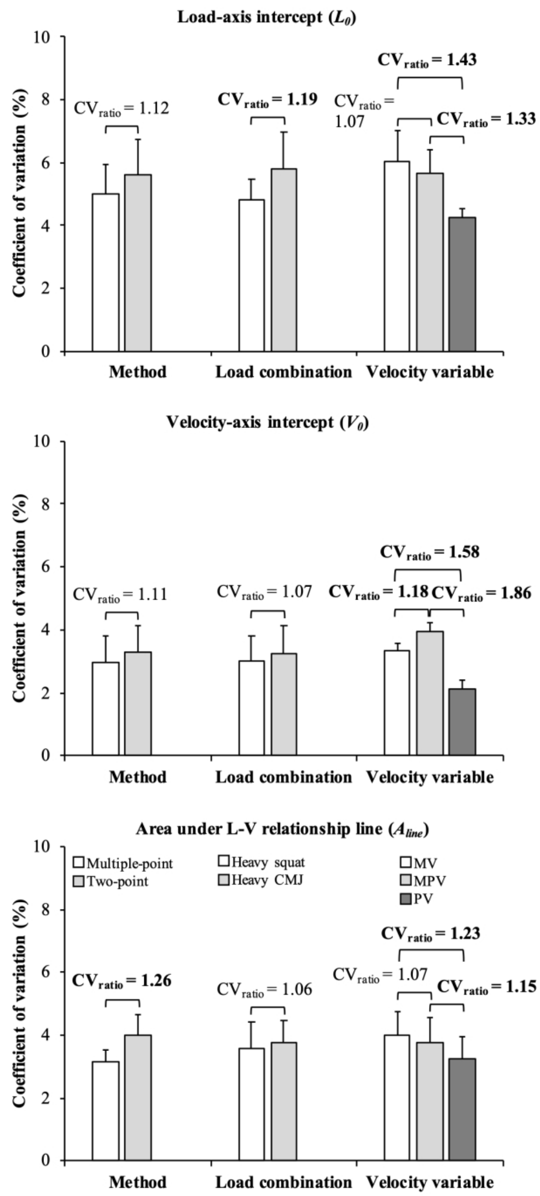

Figure 2. Reliability comparisons between the different methods (multiple-point and two-points, load combinations (heavy squat and heavy countermovement jump [CMJ]), and velocity variables (mean velocity [MV], mean propulsive velocity [MPV], and peak velocity [PV]) for the load-axis intercept (L0; upper panel), velocity-axis intercept (v0; middle panel), and area under the load-velocity (L-V) relationship line (Aline; lower panel) obtained during the countermovement jump exercise. Bars represent the average coefficient variation (CV) values and their respective standard deviations obtained combining the two load combinations and three velocity variables for the method, the two methods and three velocity variables for the load combination, and the two methods and load combinations for the velocity variable. Numbers depict the ratio between two CV (CVratio = higher value / lower value), while meaningful differences in reliability (CVratio > 1.15) are indicated in bold.

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